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THE STEADY–STATE FLOW QUALITY IN A MODEL OF A NON–RETURN WIND TUNNEL

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NOTATION

C_L	wing lift coefficient
L	total lift
n	yawing moment
q	dynamic pressure
S	wing area
V	model test section velocity or airplane forward velocity, knots
V_w	wind velocity, knots
W	airplane weight
α	angle of attack, deg
β	angle of sideslip, deg
ΔL	error in lift
Δn	error in yawing moment
Δu	maximum deviation from the mean axial velocity over 75 percent of the width on the horizontal centerline and of the height on the vertical centerline of the test section; the external wind-off value is subtracted from the wind-on value, knots
Δv	maximum lateral velocity on the centerline; the external wind-off value is subtracted from the wind-on value, positive to the starboard, knots
Δw	maximum vertical velocity on the centerline; the external wind-off value is subtracted from the wind-on value, positive up, knots
$\Delta\alpha$	error in angle of attack, deg

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SUMMARY

The structural cost of non-return wind tunnels is significantly less than that of the more conventional closed-circuit wind tunnels. However, because of the effects of external winds, the flow quality of non-return wind tunnels is an area of concern at the low test speeds required for V/STOL testing. The flow quality required at these low speeds is discussed and alternatives to the traditional manner of specifying the flow quality requirements in terms of dynamic pressure and angularity are suggested. The development of a non-return wind tunnel configuration which has good flow quality at low as well as at high test speeds is described.

INTRODUCTION

NASA has been investigating the usefulness and practicability of a new full-scale V/STOL wind tunnel (ref. 1). The Ames, Langley, and Lewis Research Centers are currently conducting design studies for this facility. During these studies the feasibility of using a non-return wind-tunnel configuration was established. The investigation performed at Ames Research Center which helped establish this feasibility is described herein. A more detailed description of this investigation is presented in reference 2.

To illustrate why a non-return configuration should be considered, the characteristics of non-return and closed-circuit wind tunnels are compared in figure 1. There are two advantages that the non-return circuit holds over the closed-circuit: No purging of contaminants such as engine exhaust gases and heated wind tunnel air is required; and the structural cost is potentially 20 to 30 percent less. The efficiency of a non-return wind tunnel can be as good as that of a comparable closed-circuit wind tunnel since approximately the same power is lost out of the exhaust of a non-return facility as is lost through the corners of a closed-circuit facility. However, the efficiency of a non-return wind tunnel is dependent on the end treatment required to reduce the effects of external winds on test-section flow quality to an acceptable level. Because of the effects of external winds, the flow quality of non-return wind tunnels is an area of concern at the low test speeds required for V/STOL studies.

Many non-return wind tunnels have been built. (See for example refs. 3 through 9.) However, these tunnels have had one or all of the following problems: low efficiency, sensitivity to external winds, or very large structures for wind shielding. The purpose of the work described herein was to develop a non-return wind tunnel configuration which had good low-speed flow quality, high efficiency, and an economical structure.

To evaluate the flow quality achieved at the low test speeds of interest for V/STOL aircraft alternatives to the traditional manner of specifying the flow quality requirements in terms of percentage of dynamic pressure and angle of attack are suggested. Results of model tests are described and evaluated for the wind conditions at a specific site.

FLOW QUALITY CRITERIA

Before the flow quality achieved by a wind tunnel can be properly evaluated it is necessary to have a flow quality criterion. Conventional criteria are not appropriate for V/STOL aircraft testing. This is illustrated in figure 2 where the error in axial velocity, Δu, is shown as a function of test velocity, V, for the conventional flow quality criterion of $\frac{\Delta u}{V} = 0.005$. At zero velocity no error is allowed, which is, of course, unrealistic.

To aid in developing a flow quality criterion for tests of V/STOL aircraft the flow quality required to establish an accurate measurement of lift for a lift-engine VTOL aircraft was examined. It was assumed that there was no interference between the engines and wing, and that the engine performance was unaffected by the flow quality. The characteristics of the assumed airplane are illustrated on the left of figure 3. Lift-to-weight ratio is shown as a function of forward speed for a wing loading of 4788 nt/sq m (100 lb/sq ft). During low speed flight, when the engine is contributing to the lift, a wing lift coefficient of 1 was used.

As pointed out previously, conventional flow quality criteria are not appropriate for the low speeds required for testing V/STOL aircraft. This is further illustrated on the right side of figure 3 which shows the error in lift measurement for the hypothetical VTOL airplane due to the conventional flow quality criteria of $\Delta\alpha = \pm\ 0.1$ degrees and $\frac{\Delta u}{V} = 0.005$ applied uniformly across the model. (The equation for $\frac{\Delta L}{L}$ used was $\frac{\Delta L}{L} = \frac{C_L}{W/qS}\left[\frac{2\Delta u}{V} + \frac{\Delta\alpha\left(\frac{\partial C_L}{\partial\alpha}\right)}{C_L}\right]$; $\frac{\partial C_L}{\partial\alpha}$ was assumed to be 0.08/deg.) The use of this criteria implies an increase in the allowable error in lift with increase test velocity; it is about 1 percent at 120 knots (62 m/sec) and 2 percent at about 200 knots (103 m/sec). As the velocity is reduced to the values appropriate for V/STOL testing the error in lift becomes much smaller than is required, indicating that the flow quality is overspecified.

In figure 4 alternate flow quality criteria for axial velocity are compared. The error in axial velocity is shown as a function of test velocity. (The error in angle of attack was assumed to be zero for this case.) The conventional criterion of $\frac{\Delta u}{V} = 0.005$ (reference 10) is shown as a solid line. In the upper plot a curve representing a 1 percent error in lift for the hypothetical airplane already described $\left(\Delta u = \frac{\Delta L}{L}\,\frac{W/qS}{C_L}\,\frac{V}{2}\right)$ is compared with the conventional criterion. At the higher velocities where all of the lift is from the wing $\left(C_L = \frac{W}{qS}\right)$ the curve matches the conventional criterion. During low speed flight where part of the lift is from the engines (velocity below about 170 knots (87 m/sec), $C_L = 1$); the error in velocity corresponding to a 1 percent error in lift increases as the velocity is decreased and is significantly higher than specified by the conventional criterion. This further indicates that the flow quality for V/STOL testing can be relaxed significantly from the conventional criterion as the test velocity is reduced.

Specifying the required precision of lift measurement is not a convenient flow quality criterion because the corresponding values of flow perturbations Δu, Δw, and Δv are dependent on the type of aircraft being considered (e.g. jet-lift VTOL, jet-flap STOL, rotary wings, etc.). Additional analysis for V/STOL aircraft with lower wing loadings and/or low disc-loading propulsion systems have indicated that a more stringent criterion than that shown at the top of figure 4 is desirable. In view of this, a constant error in axial velocity of ½ knot (0.26 m/sec) is tentatively proposed for the low-speed region as shown at the bottom of figure 4.

It does not seem likely that for V/STOL wind-tunnel testing an accuracy in axial velocity greater than ± ½ knot (0.26 m/sec) would be required. During flight testing the error in velocity is usually significantly greater than this. If the velocity is determined very carefully in flight the accuracy is on the order of ± 1 knot (0.51 m/sec) (reference 11). Typically, however, the accuracy is more like ± 2 to 3 knots (1.03 to 1.54 m/sec).

Rather than specify flow angularity in terms of angle of attack and sidewash as is conventionally done, it is tentatively proposed to specify vertical or lateral velocity. Figure 5 shows a proposed criterion for vertical velocity. Here the vertical velocity, Δw, is shown as a function of test section velocity. At low test speeds a criterion of ± ½ knot (0.26 m/sec) is proposed as shown. Conventional criteria for angularity generally range from 0.1 to 0.25 degrees (reference 10); this is shown as a shaded band. The curve representing a 1 percent error in lift for the hypothetical airplane previously described is shown at the upper right.

$$\left(\Delta w = \frac{V}{57.3}\left(\frac{\Delta L}{L}\right)\left(\frac{W}{qS}\right)\frac{1}{\frac{\partial C_L}{\partial \alpha}};\ \frac{\partial C_L}{\partial \alpha} = .08/\text{deg}\right)$$

A similar flow quality criterion for the horizontal plane is shown in figure 6; $\Delta v = \pm \frac{1}{2}$ knot (0.26 m/sec) at low speeds is proposed. The conventional criterion of 0.1 to 0.25 degrees sidewash is included. In addition, a curve is shown for the hypothetical airplane representing an error in yawing moment of 2 percent of the value available from the aerodynamic controls at a flight speed of 100 knots.

MODEL DESCRIPTION

Overall Geometry

The model used for the experimental study is shown in figure 7. Overall model dimensions are given in figure 8.

Inlet Geometry

Proper inlet treatment was found to be the most critical problem relative to test section flow quality. Extensive exit treatment was not required to maintain satisfactory levels of velocity deviation and low angularity. (However it was found necessary to exhaust vertically so that variations in the wind would not produce significant effects on the average test section velocity. Vertical exhausts were also recommended in references 3, 4, and 6.) Therefore, the inlet geometry is described in more detail than the exit geometry.

Figure 9 shows the inlet geometry developed. As shown there was a large screened area with flat-oval planform. Perforated plate with 40 percent porosity was placed around the periphery. On the inside of this perforated plate, was placed a grating with cells 2-by 2-by 2 inches (5.08-by 5.08-by 5.08 cm). The vertical members of the grating were aligned with the flow streamlines which existed with no external wind. Inside were streamlined roof supports also aligned with the wind-off streamlines. A constant area section with square-celled flow straighteners with a width-to-length ratio of 1:8 was located just up-stream of the contraction section. A conventional contraction section with a contraction ratio of 8:1 (designed according to reference 12) directed the flow into the test section.

TEST PROCEDURE

The flow quality studies were performed using the NASA Ames 40- by 80-Foot Wind Tunnel as the external wind source. The model was mounted on a platform above the boundary layer on the wind tunnel floor. The model was rotated to vary wind direction in increments of 22½ degrees.

These studies involved only the effects of steady-state winds with a uniform velocity distribution. It was concluded from other studies (references 4 and 13) that the steady-state wind was the critical problem and that wind gusts produced only a small effect on the turbulence of the test-section flow. Limited studies were performed with the model on the floor with the boundary layer artificially thickened to represent the Earth's boundary layer. (The boundary layer for wind over flat open country from reference 14 was simulated.) These studies indicated that the velocity profile was not important and that a uniform velocity equal to that at the wind-tunnel centerline could be used to establish wind effects on test-section flow quality.

RESULTS AND DISCUSSION

Basic Results

A portion of the test results are summarized in the next two figures. In figure 10 the effects of wind magnitude on Δu, Δw, and Δv are shown with the wind blowing head-on into the model inlet. The proposed flow quality criteria are shown for reference as cross-hatched boundaries. It is evident that Δu is more critical than Δw and Δv since at winds between 10 and 15 knots (5.1 and 7.7 m/sec) the axial velocity boundary is exceeded while the others are not. This may or may not be serious depending upon the wind conditions at the wind-tunnel site. This will be discussed in more detail later by examining the flow quality achieved for the wind conditions at Ames Research Center.

The effect of wind direction is shown for a 15-knot (7.7 m/sec) wind from directions of 0, 90, and 180 degrees in figure 11. The effects of the wind are less at 90 and 180 degrees than for 0 degrees. These results are representative of those at other wind directions.

Discussion of Test Results

Wind characteristics.- Before evaluating the flow quality achieved it is necessary to study the wind characteristics at the site of the wind tunnel. This was done for Ames Research Center by analyzing the wind records obtained at Moffett Field Naval Air Station, where Ames Research Center is located. Records for the past 25 years were analyzed. The results are summarized in figure 12 where the period of occurrence and the mean wind speed are shown as functions of wind direction. As shown the mean wind speed is quite low. In addition the wind is very directional; it is either from the northwest or from the southeast. These winds were measured at an elevation of 12 feet (3.66 m). It was estimated that the magnitude of the mean wind would be about 40 percent higher (reference 14) at an altitude of 90 feet (27.43 m) which is the centerline height of the proposed facility. This adjusted value was used for the evaluation of wind effects discussed in the next section.

Evaluation of the flow quality.- To evaluate the adequacy of the achieved flow quality the period of time that the wind would cause the flow quality boundary to be exceeded was examined. The results of this analysis are shown by the time percentages included alongside of the tabulated wind velocities in figure 11. (The wind tunnel was oriented 180 degrees to the prevailing wind. That is, the tunnel inlet would be southeast at Ames.) These values indicate the percentage of time that a 15-knot (7.7-m/sec) wind velocity would be equaled or exceeded at Ames Research Center. For example, a wind of 15 knots (7.7 m/sec) at 90 degrees would be equaled or exceeded only about 2 percent of the time. A wind of 15 knots at 180 degrees would be exceeded about 9 percent of the time. However, this would not produce any objectionable velocity perturbations in the test section. Thus the effect of the wind on the utilization of the wind tunnel would not be significant.

The Effects of Inlet Size

It was found that varying the inlet size while retaining the same basic internal geometry and the same 40 percent porosity perforated plate did not significantly affect the flow quality. However, as expected, the power loss of the inlet increased as the area ratio decreased. This is illustrated in figure 13 where the ratio of the total power of a non-return configuration to that of a closed-circuit configuration is shown as a function of the ratio of the peripheral inlet area to test-section area. At an area ratio of 30 the power required of the non-return wind tunnel is about 6 percent less than that of the closed-circuit wind tunnel, and at an area ratio of about 15 it is about 12 percent higher. (The energy ratio of the closed-circuit wind tunnel was 8.) The crossover is at an area ratio of about 20. It was estimated that, for an inlet at this crossover, the structural cost of the non-return wind tunnel would be about 80 percent of the cost of a comparable closed-circuit wind tunnel (reference 15). Thus, the non-return wind tunnel provides equivalent power efficiency and reasonable flow quality with substantially lower structural cost than the conventional closed-circuit wind tunnel.

CONCLUDING REMARKS

The flow quality required for wind tunnel tests of V/STOL aircraft at low flight speeds was examined. At these low speeds the conventional flow quality criteria of $\Delta\alpha$ and $\frac{\Delta u}{V}$ are not appropriate since they become meaningless as the free-stream velocity approaches zero. Based on a number of considerations it was concluded that velocity deviations of ½ knot (0.26 m/sec) or less would provide an adequate flow quality for tests of V/STOL aircraft up to free-stream speeds of about 100 knots (51 m/sec). Above this speed conventional flow quality criteria may be used.

Wind tunnel tests were conducted to determine the effects of external winds on the flow quality of a model of a non-return wind tunnel. The results of these tests indicated that satisfactory flow quality was achieved. Further improvements in flow quality could be obtained by further refinement of the wind-tunnel inlet concepts discussed herein.

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COMPARISON OF NON-RETURN AND CLOSED-CIRCUIT WIND TUNNELS

	NON-RETURN	CLOSED-CIRCUIT
PURGING	NOT REQUIRED	REQUIRED • EXHAUST GASES • HEATED AIR
EFFICIENCY	ENERGY RATIO 1 TO 9	ENERGY RATIO 1 TO 9
STRUCTURAL COST	POTENTIALLY LOWER	
FLOW QUALITY	SUBJECT TO WIND EFFECTS	INDEPENDENT OF WIND

Figure 1

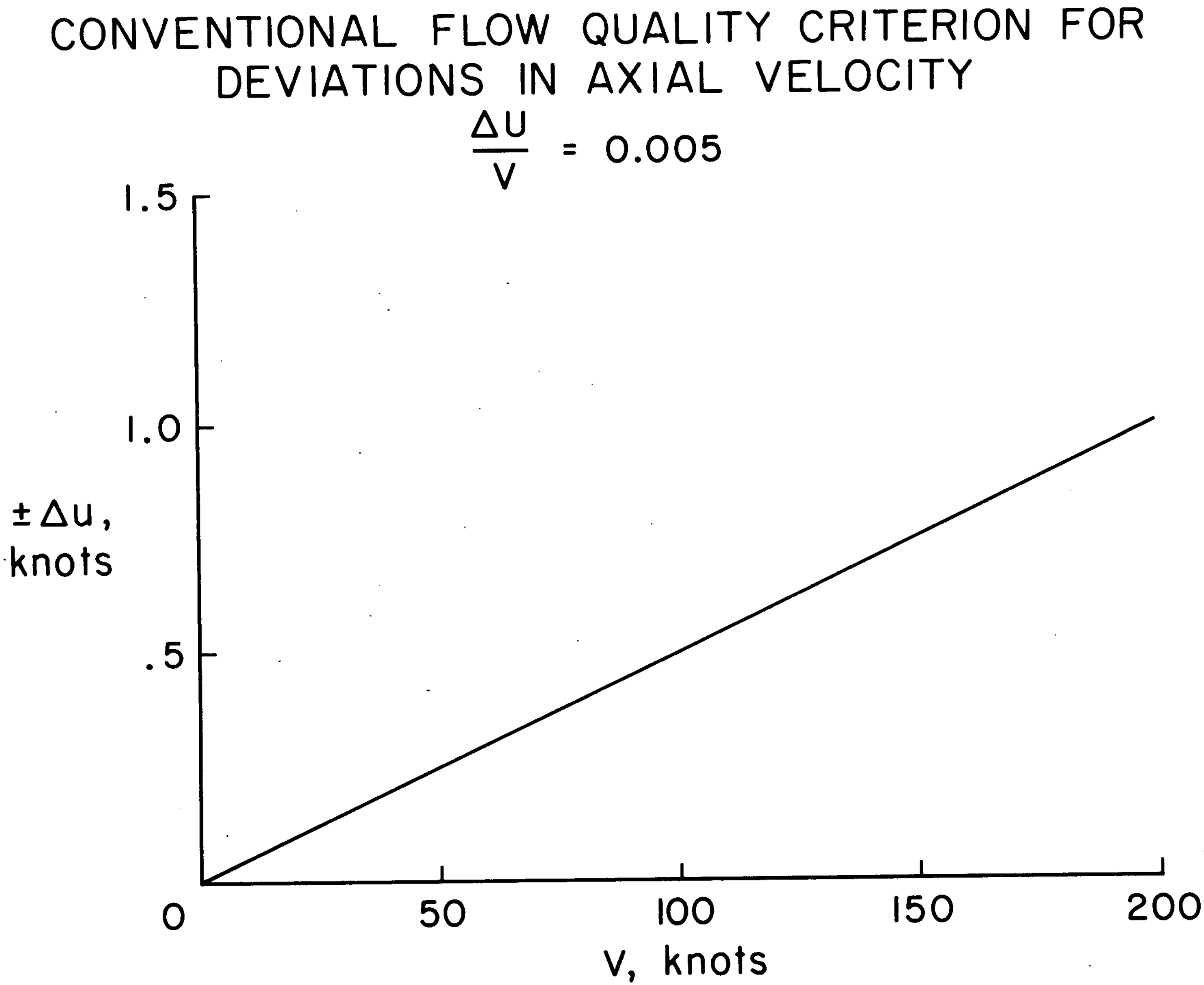

CONVENTIONAL FLOW QUALITY CRITERION FOR DEVIATIONS IN AXIAL VELOCITY
$\frac{\Delta U}{V} = 0.005$
1.5
1.0
.5
±Δu, knots
0
50
100
150
200
V, knots

Figure 2

EFFECT OF CONVENTIONAL FLOW QUALITY CRITERIA ON LIFT FOR A LIFT-ENGINE VTOL AIRPLANE; W/S=100 psf

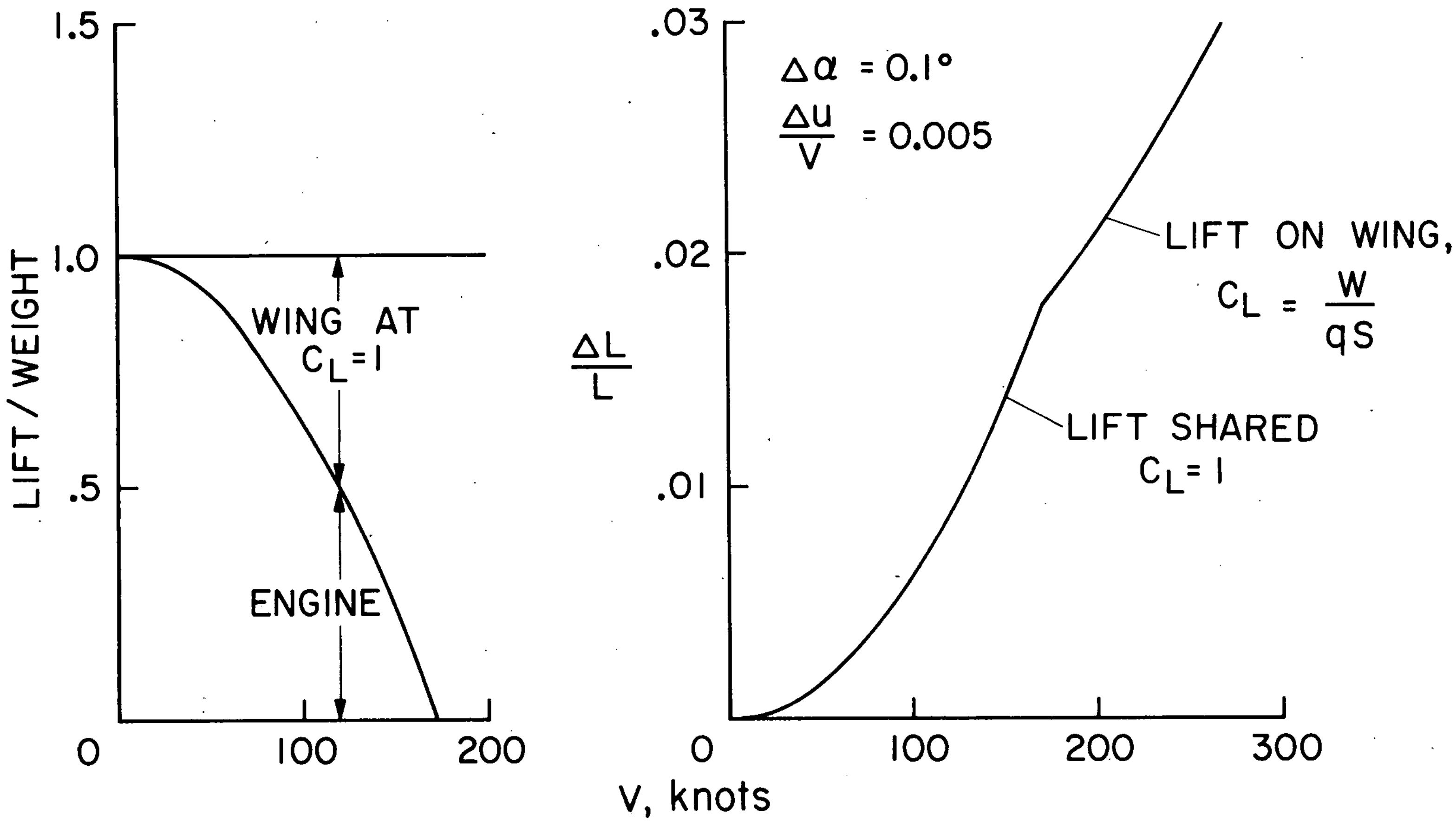


Figure 3

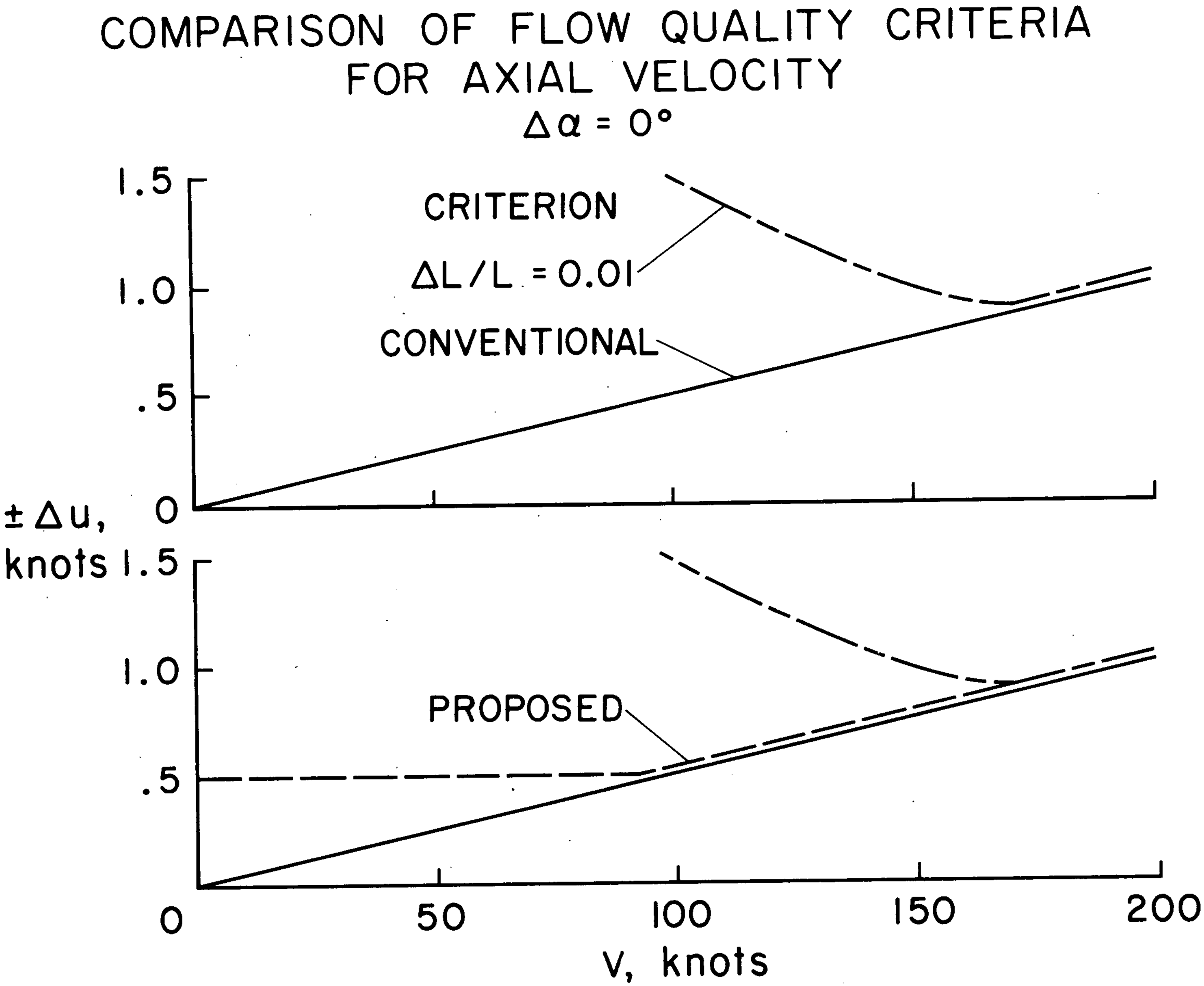

COMPARISON OF FLOW QUALITY CRITERIA
FOR AXIAL VELOCITY
Δα = 0°
1.5
1.0
.5
0
CRITERION
ΔL/L = 0.01
CONVENTIONAL
±Δu,
knots
1.5
1.0
.5
PROPOSED
0
50
100
150
200
V, knots

Figure 4

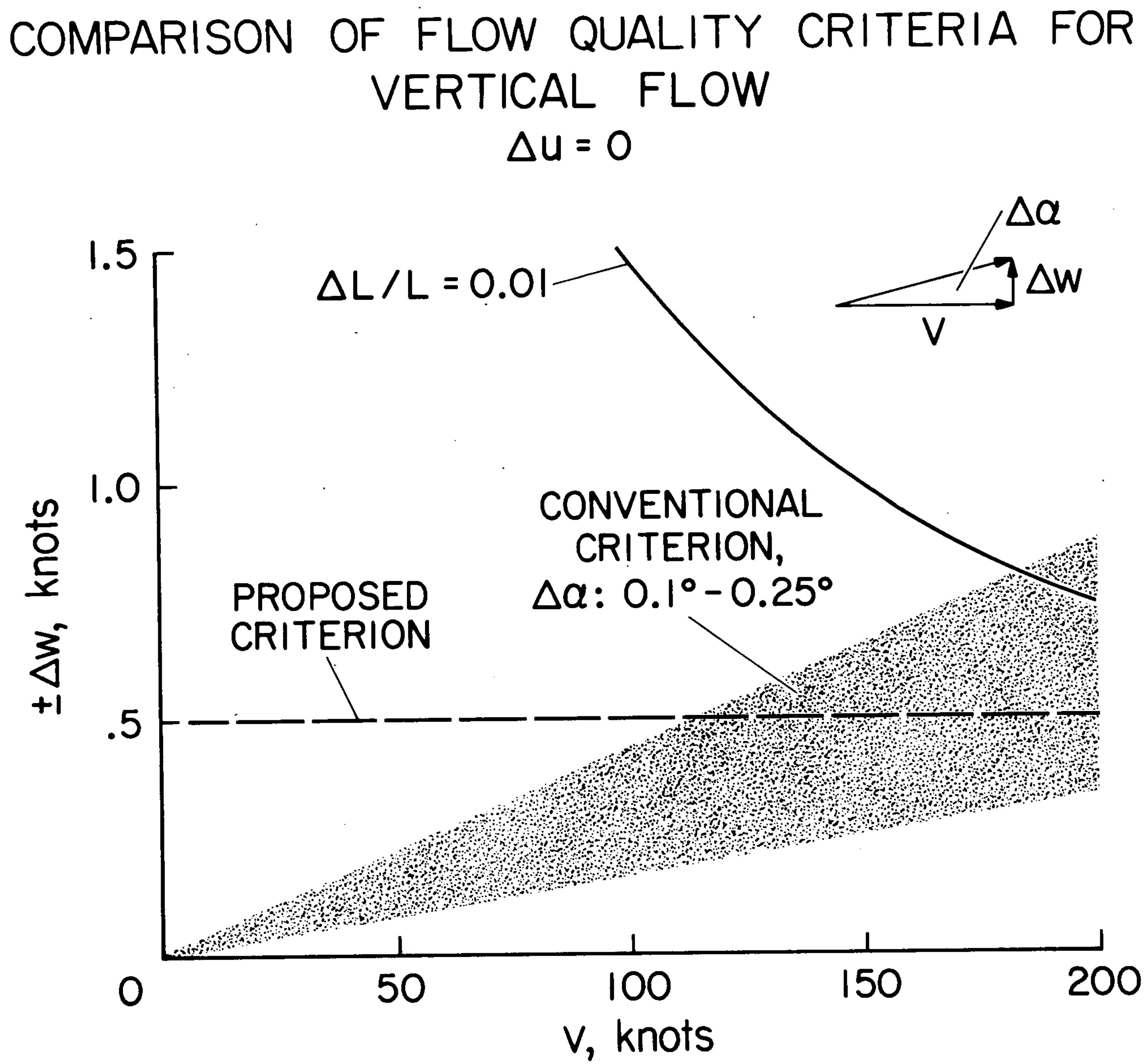

COMPARISON OF FLOW QUALITY CRITERIA FOR
VERTICAL FLOW
Δu = 0
ΔL/L = 0.01
Δα
Δw
V
1.5
1.0
.5
±Δw, knots
CONVENTIONAL
CRITERION,
Δα: 0.1° - 0.25°
PROPOSED
CRITERION
0
50
100
150
200
V, knots

Figure 5

COMPARISON OF FLOW QUALITY CRITERIA FOR LATERAL FLOW

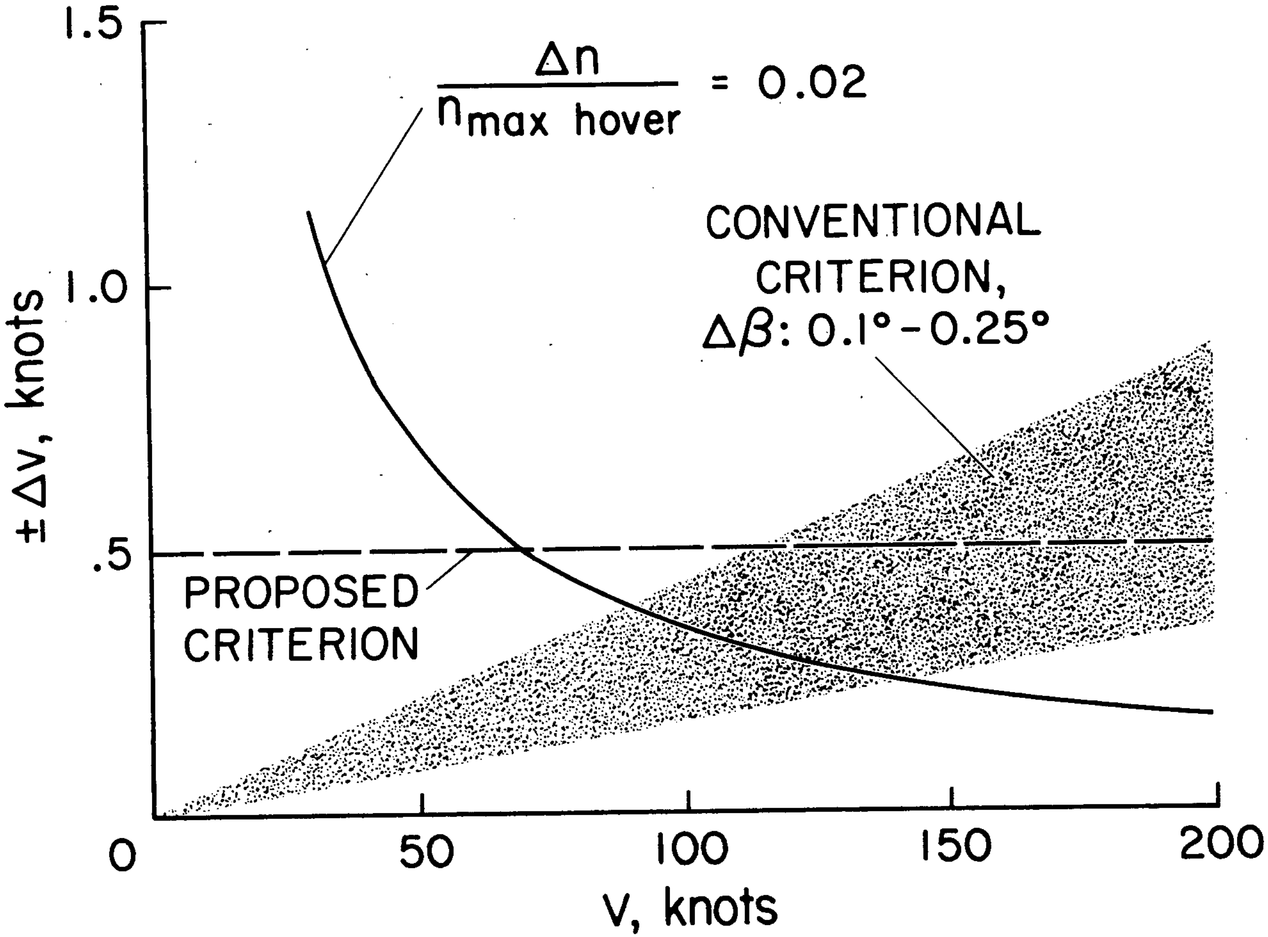


Figure 6

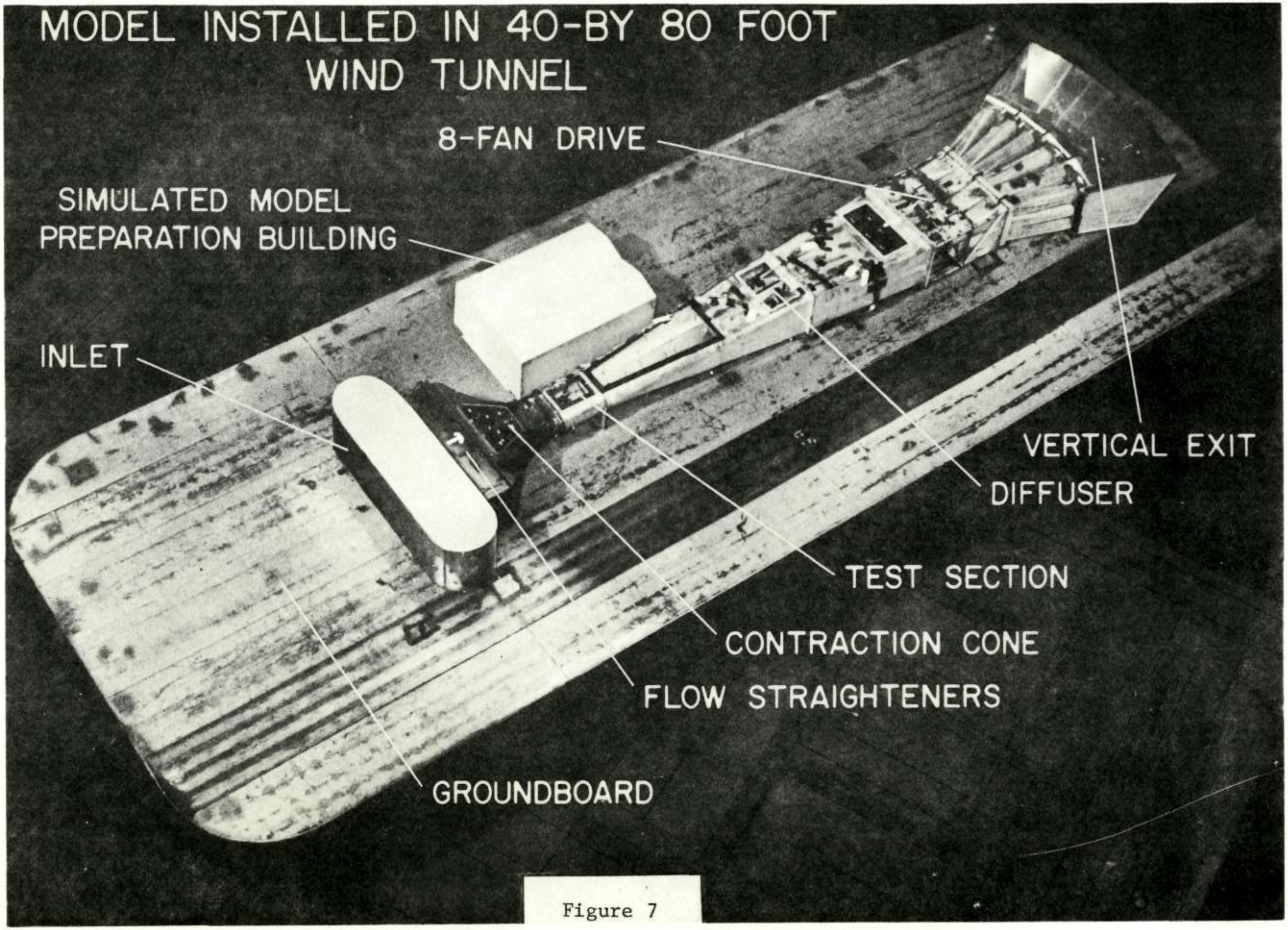
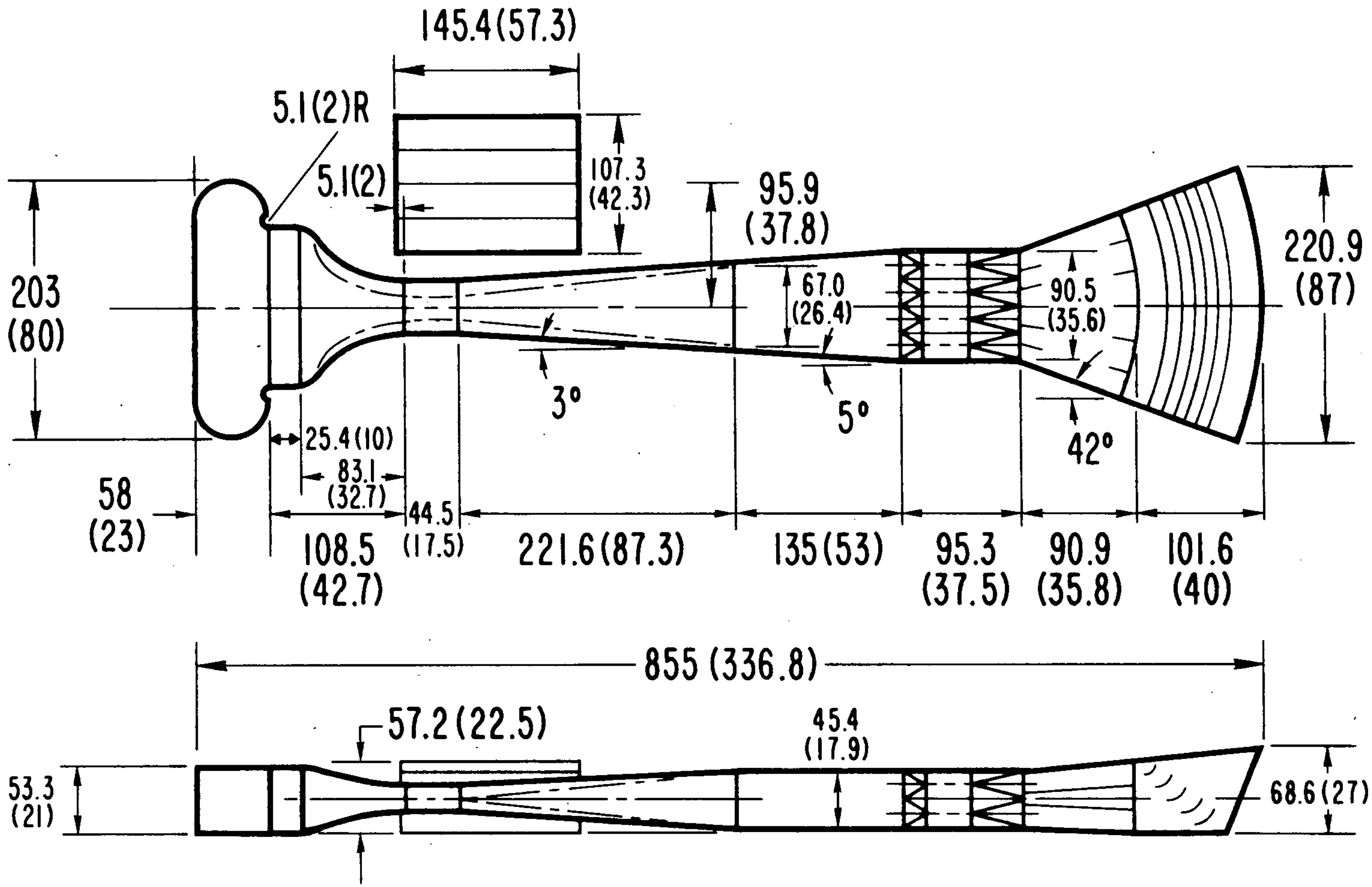

MODEL INSTALLED IN 40-BY 80 FOOT WIND TUNNEL
8-FAN DRIVE
SIMULATED MODEL PREPARATION BUILDING
INLET
VERTICAL EXIT
DIFFUSER
TEST SECTION
CONTRACTION CONE
FLOW STRAIGHTENERS
GROUNDBOARD

Figure 7



DIMENSIONS IN cm (in.)
INSIDE DIMENSIONS SHOWN

Figure 8

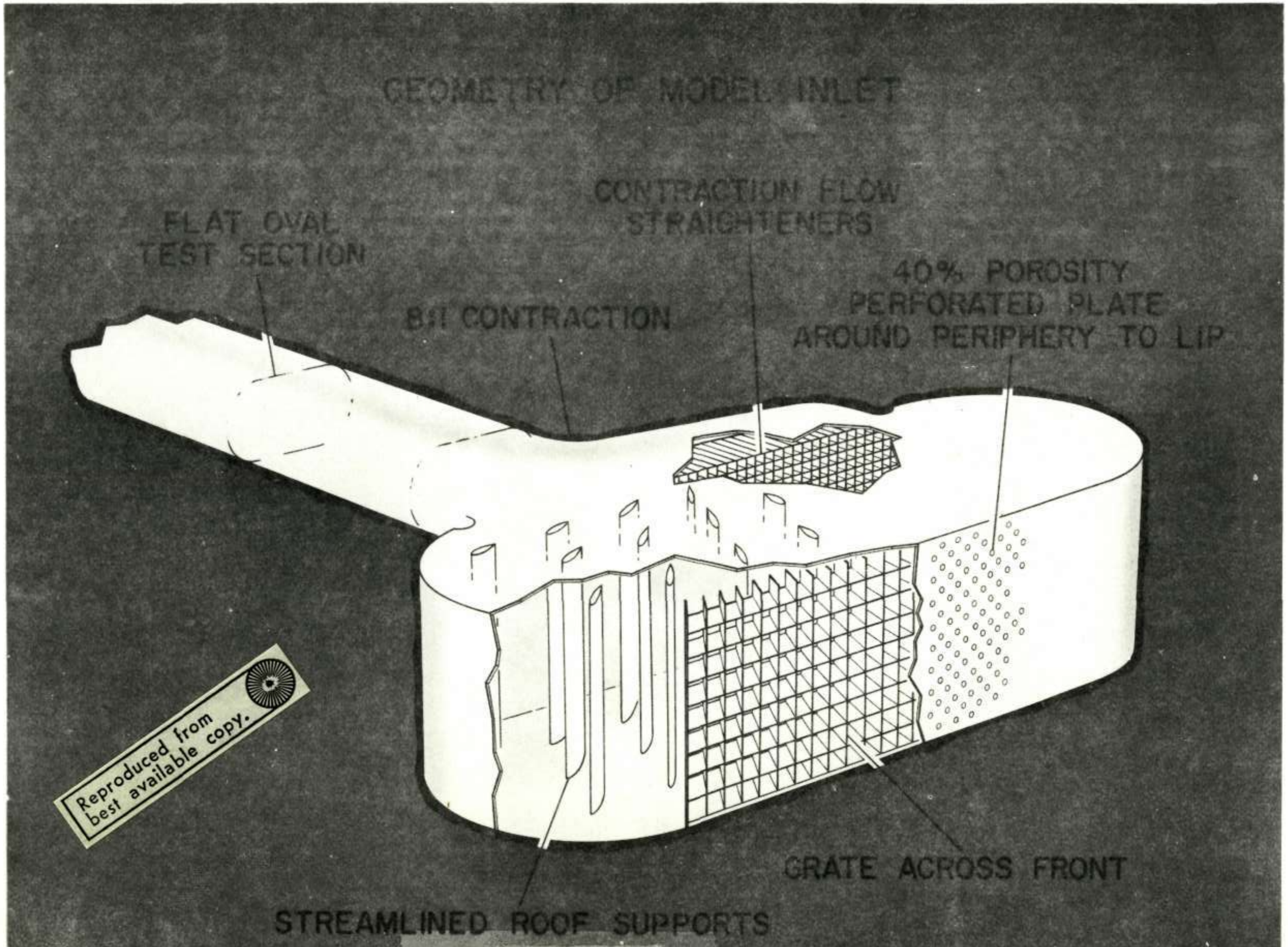

GEOMETRY OF MODEL INLET
CONTRACTION FLOW STRAIGHTENERS
FLAT OVAL TEST SECTION
40% POROSITY PERFORATED PLATE AROUND PERIPHERY TO LIP
8:1 CONTRACTION
GRATE ACROSS FRONT
STREAMLINED ROOF SUPPORTS

Figure 9

EFFECT OF WIND VELOCITY ON TEST SECTION VELOCITY DEVIATIONS WITH THE WIND HEAD ON

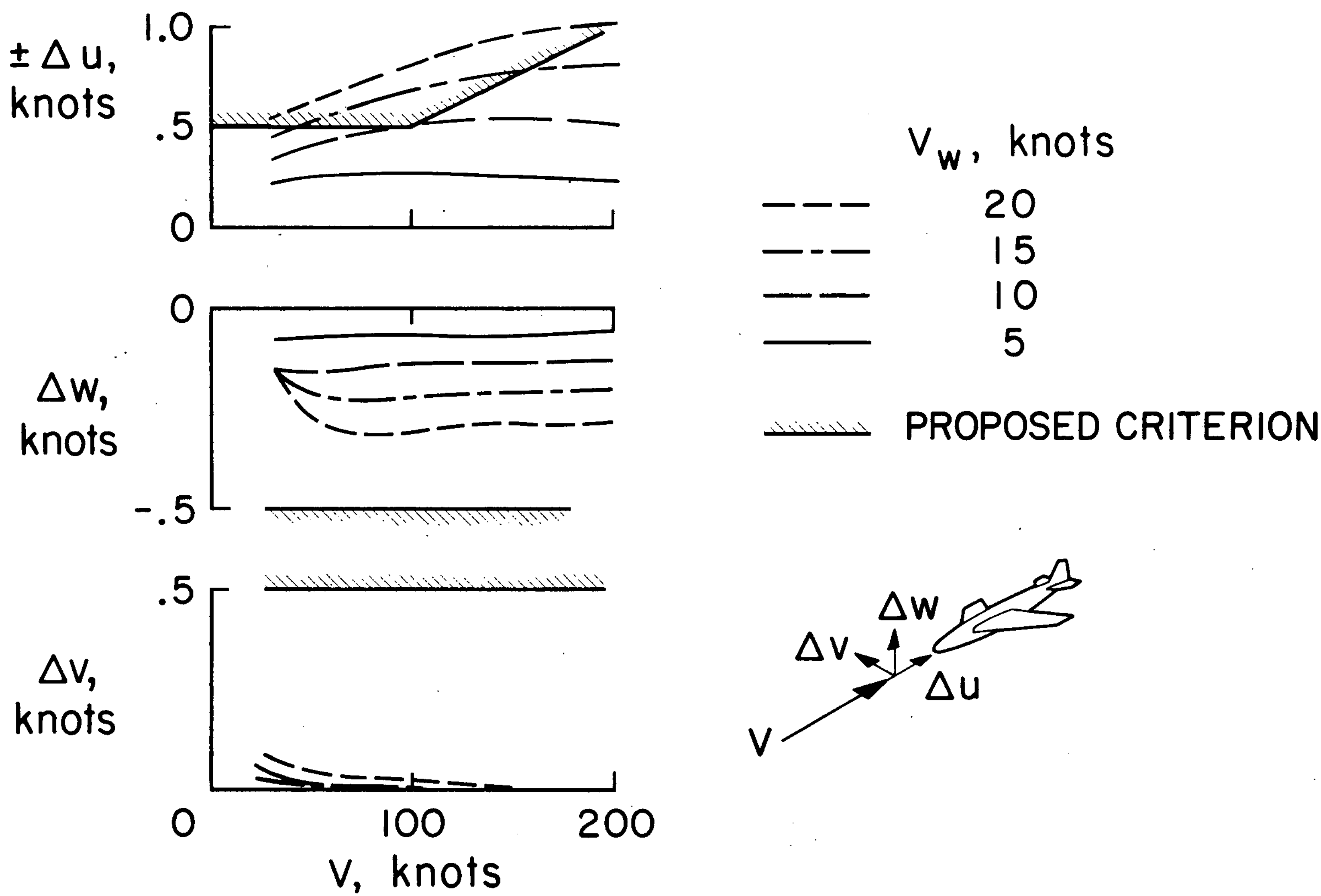


Figure 10

EFFECT OF WIND DIRECTION ON TEST SECTION VELOCITY DEVIATIONS

V_W = 15 knots

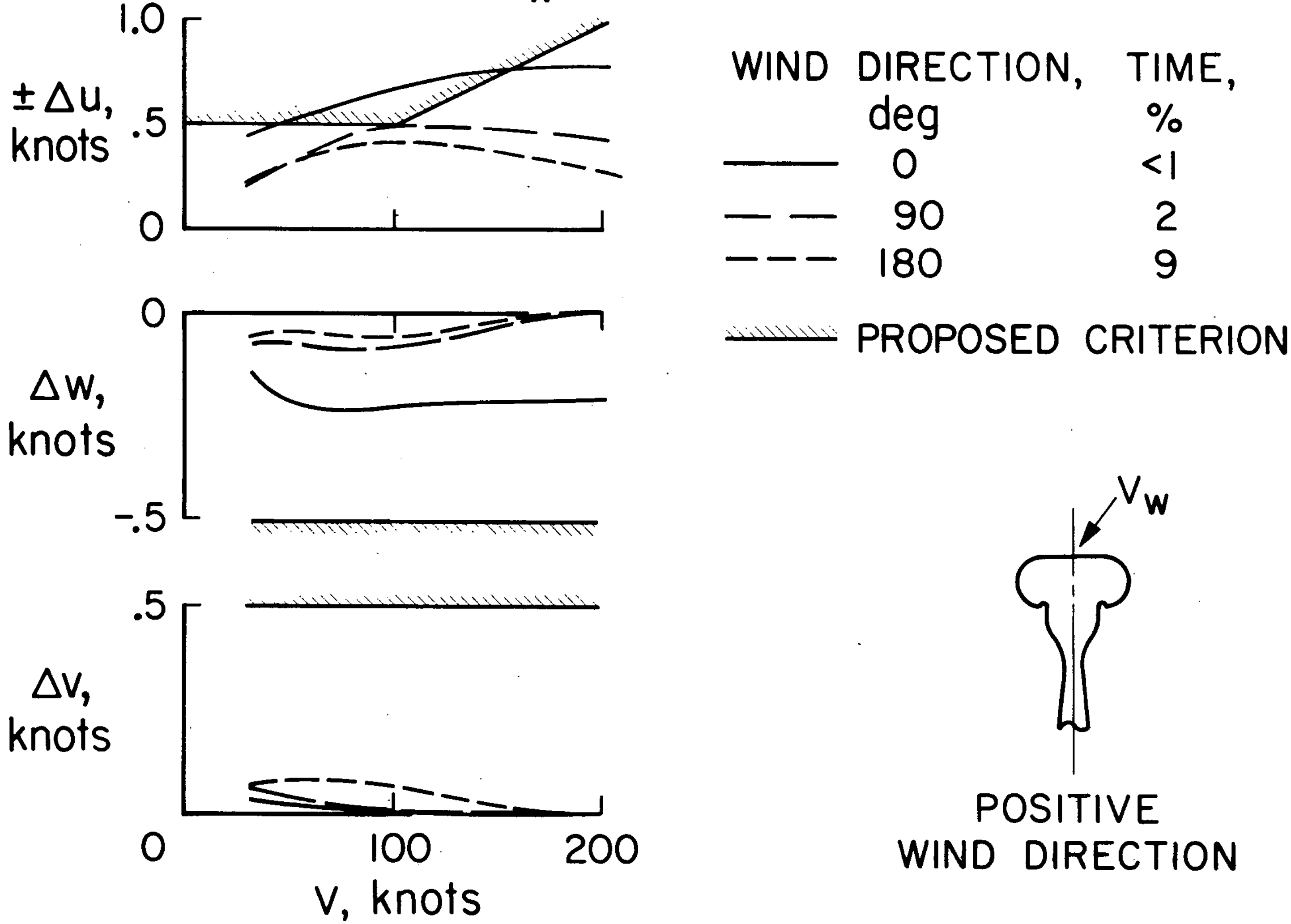


Figure 11

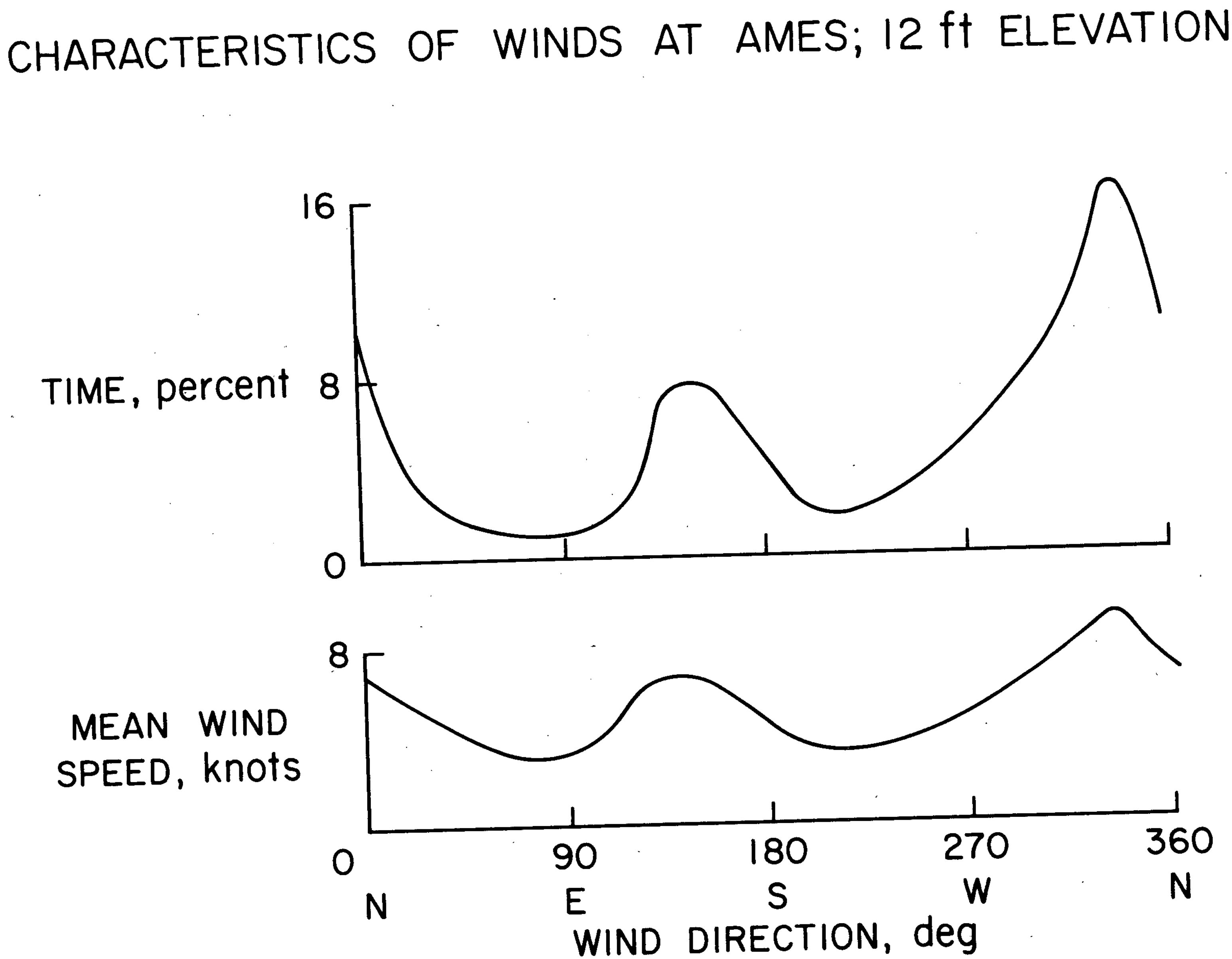

CHARACTERISTICS OF WINDS AT AMES; 12 ft ELEVATION
16
TIME, percent
8
0
8
MEAN WIND SPEED, knots
0
90
180
270
360
N
E
S
W
N
WIND DIRECTION, deg

Figure 12

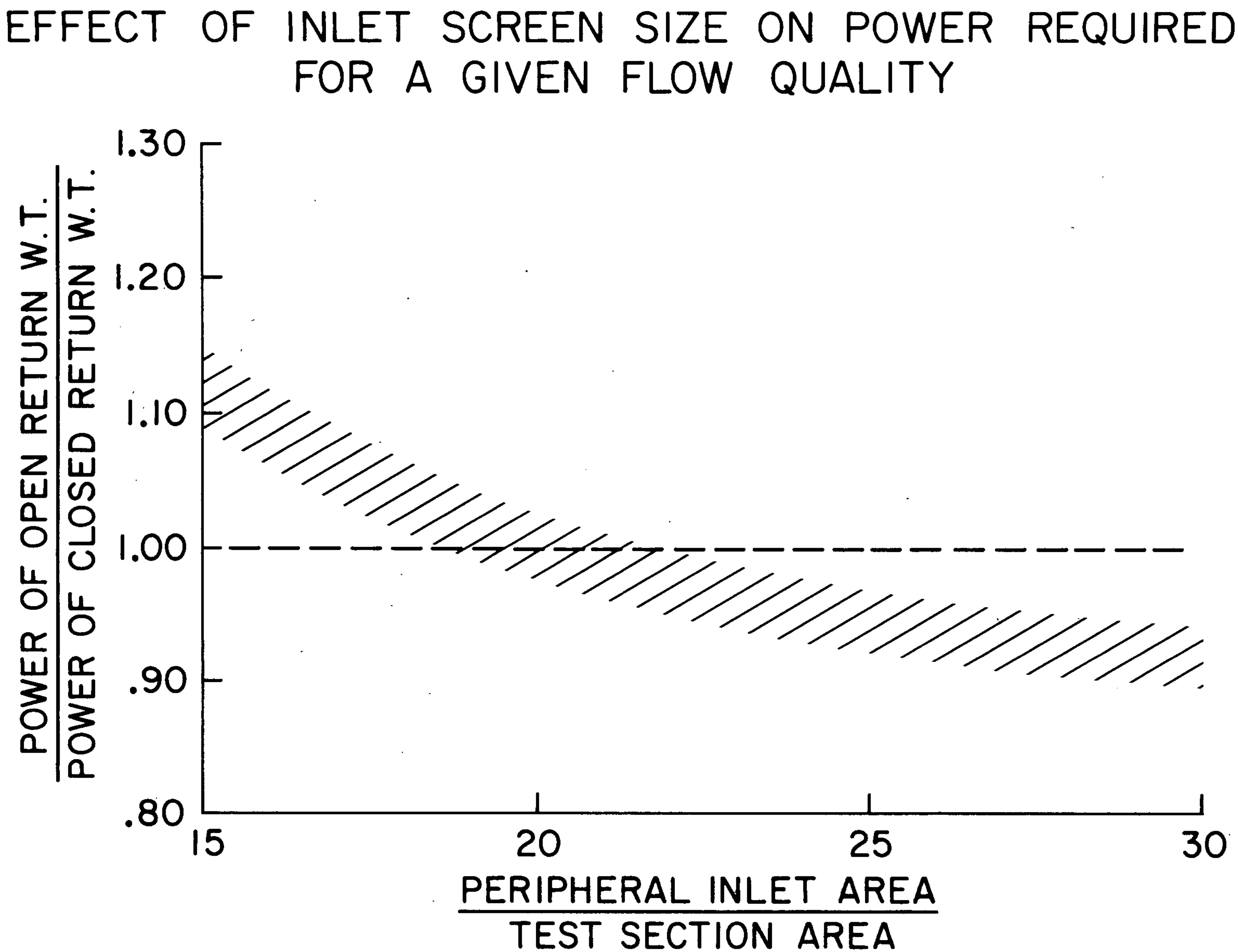

EFFECT OF INLET SCREEN SIZE ON POWER REQUIRED
FOR A GIVEN FLOW QUALITY
POWER OF OPEN RETURN W.T. / POWER OF CLOSED RETURN W.T.
1.30
1.20
1.10
1.00
.90
.80
15
20
25
30
PERIPHERAL INLET AREA / TEST SECTION AREA

Figure 13